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Benefit Analysis of Airborne GPS Occultation Approach: A Case Study for the Australian Region

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ABSTRACT

This paper aims to present a preliminary benefit analysis for airborne GPS occultation technique for the Australian region. The simulation studies are based on current domestic commercial flights between major Australian airports. With the knowledge of GPS satellite ephemeris data, occultation events for for any particular flight can be determined. Preliminary analysis shows a high resolution occultation observations can be achieved with this approach, for instance, about 15 occultation events for a Perth-to-Sydney flight. The simulation result agrees to the results published by other researchers for a different region. Of course, occultation observation during off-peak hours might be affected due to the limited flight activities.

High resolution occultation observations obtainable from airborne GPS occultation system provides an opportunity to improve the current global numerical weather prediction (NWP) models and ultimately improves the accuracy in weather forecasting. More intensive research efforts and experimental demonstrations are required in order to demonstrate the technical feasibility of the airborne GPS technology.

KEYWORDS: GPS; Airborne Radio Occultation; Simulation.

1. INTRODUCTION

Radio Occultation refers to a sounding technique in which radio or microwave signals are transmitted and pass through atmosphere before arriving at the receiver. As the signal propagates through the atmosphere, the velocity and the direction of the wave are altered due to change in the refracting index between transmission mediums (space and atmosphere). Consequently, the received signal amplitude and phase measurements are altered relative to their values that would hold without propagating through the intervening medium. By making continuous measurements, profiles of the phase variation and the amplitude variation can be generated to provide information about the refractive properties of the intervening medium. The observed atmospheric refractive index profile can then be used to monitor various meteorology parameters, such as the pressure, temperature, water vapour density, and the ionosphere electronic density.

Since the American Global Positioning System (GPS) constellation became fully operational in 1993, there has been rapidly growing interests in using the system as a continuous signal sources for radio occultation researches. Today, the GPS constellation is comprised of about 30 satellites; each is capable of transmitting L-band frequency signals (the L1 carrier frequency of 1575.4 MHz, the L2 carrier frequency of 1227.6 MHz, and the L5 carrier frequency of 1176.45 for the modernized GPS satellites in the near future) (Parkinson 1996). With the signal available at a worldwide scale and free of service charge, GPS based meteorology has become an active field of research in the past decade (Businger, Chiswell et al. 1996). In addition to the GPS, the Russian Global Navigation Satellite System (GLONSS) and the future European Galileo system can also be used for meteorological sensing.

Over the years, GPS meteorology researches have been conduced through two main approaches: space-based and ground-based (Bevis, Businger et al. 1992). For the space-based approach, GPS receivers onboard of Low Earth Orbit (LEO) satellites were used to collect signal transmitted from GPS satellites during atmospheric occultation events. By measuring the change in the carrier phase over the entire occultation event (approx. 60 ~ 100 seconds for the neutral atmosphere) (Melbourne 2005), the atmospheric refractive index can be determined as a function of altitude. The refractive index profile is then used to derive temperature and pressure distribution within the stratosphere and water vapour distribution within the troposphere. On the other hand, the ground-based approach involves data collection at fixed ground locations with dual frequency GPS receivers. As the GPS signal propagates through the atmosphere, significant signal delays are experienced and recorded by the GPS receiver. These delays are strongly sensitive to the total quantity of water vapour integrated along the signal path. This integrated water vapour is a representation of the total latent heat available in the column from the vapour, and as such it has the potential to provide a powerful constraint to Numerical Weather Prediction (NWP) models (Kuo, Guoa et al. 1993; Kuo, Zou et al. 1996) and in weather analysis. In recent years, researchers have also investigates the potential of setting up a ground monitoring station on top of mountains. This is a slight deviated approach ground-based method and is referred to as the mountain-based approach(Zuffada, Haji et al. 1999). With a GPS receiver installed on the top of mountain and a down-looking GPS antenna, tropospheric water vapour profile can be estimated below the altitude in which the receiver is located (Aoyama, Shojiy et al. 2003; Sun, Bai et al. 2007).

Apart from the conventional approaches, researchers have proposed the idea of using airborne platform for GPS meteorology researches (Haase and Lesne 2001; Lesne, Haase et al. 2002;

Yoshihara, Fujii et al. 2004). Similar to the mountain-based approach, data are collected from a back-looking or side-looking antenna to derive water vapour profile that is below the operating altitude. However, instead of a stationary location, the GPS receiver and antennas onboard aircraft are operated in constant moving mode during a flight mission. The main advantage of this approach is that data can be collect anywhere around the globe as long as it can be reached by an air vehicle. Thus, this approach can be used provide water vapour profiles in areas, such as above oceans, where traditional ground-based or mountain-based approaches are not possible. Additionally, with commercial flights travelling globally in a daily basis, airborne-based approach has the potential to benefit the GPS meteorology community at a fraction of cost than setting up a satellite constellation. However, as the technology is still of a relatively new concept, more experiments and studies are required to demonstrate the concept and benefits of the approach.

The objective of this research is to explore the benefits of airborne occultation platform in Australian region through simulation study. Section 2 briefly outlines the concept of radio occultation with illustrations, equations, and results achieved by previous researchers. Section 3 provides the methodology in which simulation is conducted. Simulated data are analysed for the occurrence of occultation events as the result of this study. Finally, Section 4 concludes with findings of this simulation study.

2. Concept of the Airborne-based GPS Occultation System

The use of aircrafts for radio occultation was firstly proposed by Hass and Lesne (2001) as a complementary technique to overcome limitations of the spaceborne radio occultation system. With a properly equipped air vehicle, an airborne GPS radio occultation system has the ability to provide a better estimate of water vapour profile up to flight level and the ability to provide high resolution regional and global observations. The latter is unachievable with the current ground and mountain-based systems as both of them cannot be setup in oceanic regions. A constellation of spaceborne GPS receivers could provide similar degree of resolution; however, the cost involved in setting up such a system is significantly higher than the airborne approach.

In order to achieve the full ability of the airborne GPS occultation system, researchers have identified several requirements. Firstly, a dual frequency GPS configuration is required to remove the ionospheric effect. Secondly, back-looking or side-looking GPS antennas are required to provide continuous GPS signal tracking from low and negative elevation angles. Finally, high precision navigation equipments are required to remove the effects of aircraft motion with respect to the satellite from the raw GPS carrier phase data.

The fundamental principle of airborne GPS occultation system involves sub-horizontal line-of-sight (LOS) signal observations as the GPS satellite rises or sets behind the Earth relative to the receiver. Figure 1 below illustrates an exaggerated form of a typical airborne-based GPS occultation scenario.

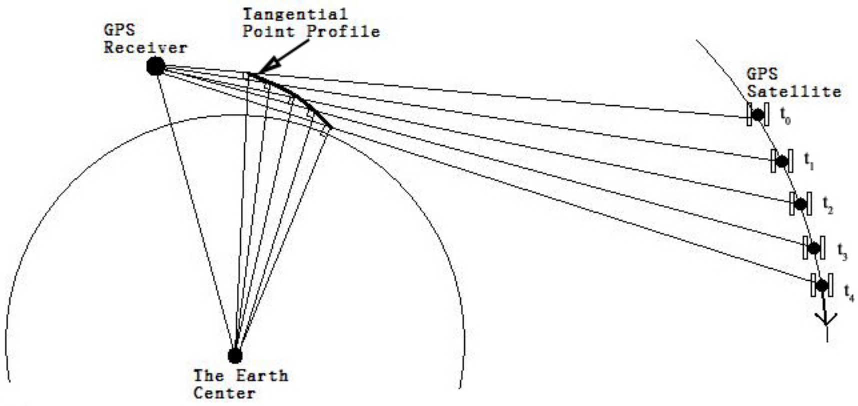

Figure 1. Illustration of tangential point profile during a GPS occultation event

When the GPS receiver tracks a GPS satellite as it occults the Earth's atmosphere, the arrival time of the signal is delayed due to the refractive bending and slowing as it passes through the atmosphere. By measuring the change in carrier phase over the entire occultation event, the atmospheric refractive index can be determined as a function of tangential point altitude. Tangential point is defined as the point closest to the Earth's surface along the signal propagation path; a series of such point determined during the entire occultation event is defined as the tangential point profile and shown in Figure 1. Thus, utilizing the relationship between atmosphere refractive sensitivity and water vapour pressure, airborne GPS occultation observations can provide estimates of tropospheric water vapour profile below the receiver location along the tangential point profile (Yoshihara, Fujii et al. 2004).

This preliminary study aims to investigate the benefits of airborne GPS occultation system in terms of the occultation event distribution, basic concept in determining the tangential point is presented below. Occultation calculation and analysis are referred to the existing work by Haase and Lense (2001).

Figure 2 shows an illustration of the geometry for estimating the tangential point, at which the tropospheric profiles can be derived from the airborne and ground GPS measurements. For sake of simplicity, it is assumed that the propagation path from GPS satellite to the GPS receiver is along a straight line. Signal bending due to the atmosphere refractivity is small is ignored in this case.

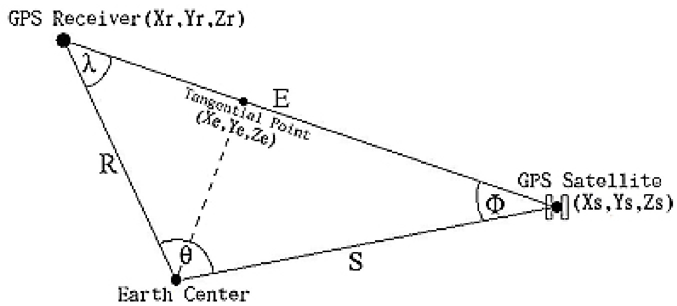

Figure 2. Geometry for estimating the tangential point

In order to determine the tangential point as illustrated in Figure 2, angle between GPS satellite to GPS receiver vector and GPS satellite to Earth centre vector must be firstly calculated. This angle is denoted as Φ as shown in Figure 2. Firstly, the Law of Cosines is rewritten with respect to Figure 2 as follow:

$$R^2 = E^2 + S^2 - 2ES \times \cos(\Phi) \quad (1)$$

where: R is the distance between GPS receiver and the Earth centre, S is the distance between GPS satellite and the Earth centre, and E is the distance between the GPS satellite and the GPS receiver.

By re-arranging equation, angle Φ can be calculated as:

$$\Phi = \cos^{-1}\left(\frac{E^2 + S^2 - R^2}{2ES}\right) \quad (2)$$

Thus, distance between the GPS satellite and the tangential point can be calculated by:

$$D = \frac{E^2 + S^2 - R^2}{2E} \quad (3)$$

Finally, coordinate of the tangential point is determined as:

$$TP = P_{GPS} + D \times \frac{\overrightarrow{P_{GPS}P_{REC}}}{E} = P_{GPS} + \overrightarrow{P_{GPS}P_{REC}} \times \frac{E^2 + S^2 - R^2}{2E^2} \quad (4)$$

where TP is the coordinate of the tangential point, P_{GPS} is the coordinate of the GPS satellite, $\overrightarrow{P_{GPS}P_{REC}}$ is the vector from the GPS satellite to the GPS receiver.

Hass and Lense (2001) had investigated the airborne system concept demonstrated using simulated flights over Atlantic Ocean. With fourteen flights across the Atlantic Ocean, their simulation result shows a total number of 225 occultation events can be obtained. It averages to 1 occultation every 220 kilometres of flight or 22 occultations for an 8 hours flight. In comparison, a single LEO spacecraft equipped with a GPS receiver is only capable of providing approximately 8 occultations per day over the same region. Thus, a constellation of 25 LEO satellites is required if the same degree of occultation density is to be achieved.

Haase and Lense (2001) also studied differences in the occultation geometry between the spaceborne and the airborne GPS occultation. First of all, due to the much lower receiver velocity, the occultation duration observed by the airborne-based system is determined primarily by the time it takes for the GPS satellite to set. Typically, occultation duration observed by airborne-based system is in the range of 8 to 25 minutes depending on the direction of travel of both the GPS receiver and the GPS satellite. In comparison, a typical satellite-based occultation is only for duration of 30 to 100 seconds. Secondly, due to large azimuthal movement range of the GPS satellites and the low receiver velocity, there is a significant horizontal drift of the tangent point over the course of an airborne-based occultation. The horizontal drift varies from about 200 to 470 km, as opposed to a typically drift of about 50 to 200 km from LEO occultation is reported by Haas and Lense (2001).

This simulation is conducted for the Australian region. This is identified as the initial evaluation phase for proposing an airborne GPS occultation platform. Simulated results will be analysed with respect to the distribution of occultation obtained by Haase and Lense as bench mark in their previous results. By doing so, it is hoped to further strength the benefits of airborne GPS occultation system. The simulation methodology and results are presented in the next section.

3. Simulation Methodology and Result

In order to understand the benefit of airborne-based GPS occultation for Australian region, Qantas domestic flight services were chosen and simulated as the testing platform. Fourteen domestic and international airports were chosen based on the flight frequency as well as their location to maximize the coverage area. Qantas direct flights between these airports were chosen and simulated for 14 November, 2006. Table 1 below provides the chosen airports and their precise location in terms of longitude, latitude and altitude.

AIRPORT NAME	**LONGITUDE (deg)**	**LATITUDE (deg)**	**ALTITUDE (m)**
Alice Springs	-23.8069	133.9022	1789
Brisbane International	-27.3842	153.1175	13
Cairns International	-16.8858	145.7553	10
Mt. Isa	-20.6639	139.4886	1121
Townsville	-19.2525	146.7653	18
Darwin	-12.4167	130.8667	0
Hobart	-42.8361	147.5103	13
Melbourne International	-37.6733	144.8433	434
Adelaide International	-34.9450	138.5306	20
Broome	-17.9500	122.2333	0
Karratha	-20.7122	116.7733	29
Perth International	-31.9403	115.9669	67
Canberra	-35.3083	149.1939	1888
Sydney International	-33.9461	151.1772	21

Table 1. Selected Australian domestic airport coordinates

For this simulation study, direct Qantas domestic flights between the selected airports were considered as the only data source. Flight schedules were gathered from the official Qantas website and a total number of 376 flight services were simulated. Note that other airline carriers and also transferred flights were ignored, but can be later considered for future study if necessary.

Flight path simulation was done by assuming aircrafts are flying at an altitude of 10km above the Earth's surface with a constant velocity. With a known flight duration (arrival time minus the departure time), aircraft velocity for a particular flight route can be estimated by dividing the flight distance by the flight duration. Additionally, aircrafts are assumed to be flying on the great circle path which is defined as the shortest path on the surface of a sphere between two points on that sphere. Finally, aircraft are assumed to be flying on great circle path with a constant velocity determined by averaging the flight time and the distance between the departure and arrival airport. The simulation implemented in Matlab programming environment version 7 where built-in functions are available for estimating the great circle path. Figure 3 below shows the selected airport location as well as the interconnecting flight routes between these airports.

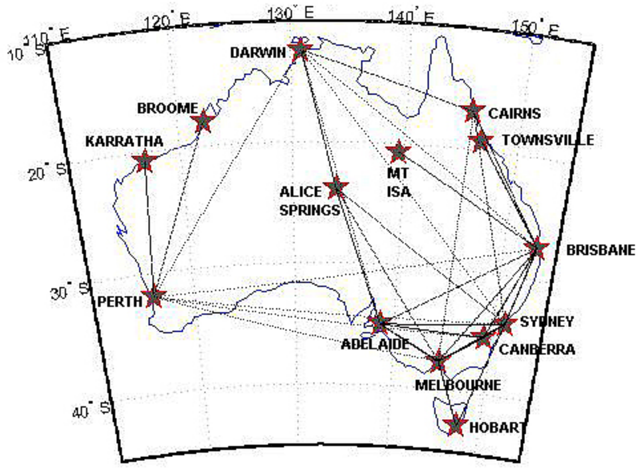

Figure 3. Plot of the selected Australian domestic airports and flight paths for interconnecting routes

Occultation results for flights between Perth and Sydney were chosen as example to demonstrate the results in the simulation. The path is one of the longest domestic flight routes in the simulation. The left diagram of Figure 4 shows the airport locations (red stars), the flight path between airports (black line connecting two airports), and occultation distribution simulated for this flight service that departs Perth at 5:50am and arrives Sydney at 12:55pm. A total number of 15 occultation events are observed for this scenario. On the right hand side of Figure 4, an accumulated occultation event simulated for the Perth to Sydney flight route is shown for 14 November, 2006. The star sign shows the location of the airport, the dark black line outlines the flight path between two airports, and the grey line represents the distribution of occultation events. During the entire simulation campaign, there are 6 exchanging flight services between these two airports. The total number of occultation events for these 6 flights are calculated as 80.

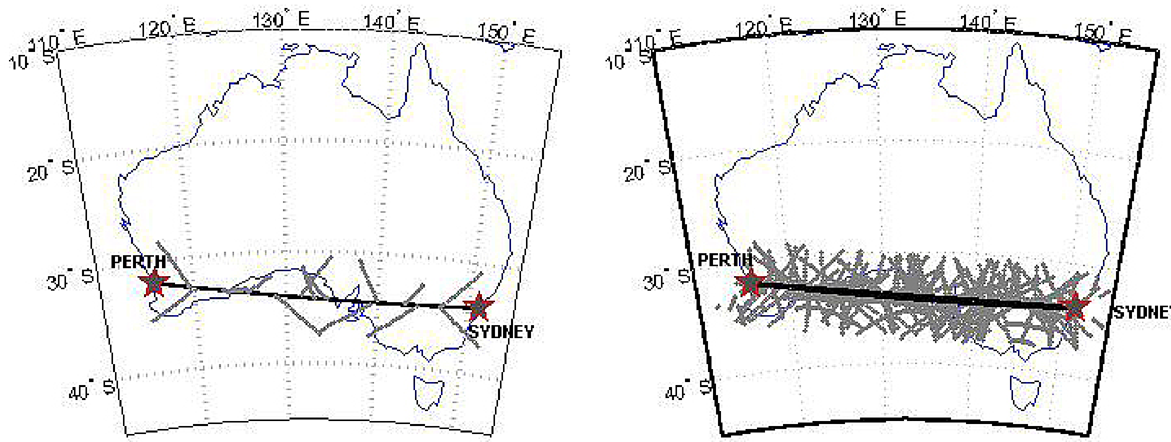

Figure 4. Flight path for the aircraft that depart Perth at 5:50 am arrive Sydney at 12:55 pm (Black line) and the estimated tangential profile for the flight (Gray line) [Left diagram]. Flight path for all flights between Perth and Sydney on 14 November, 2006, black line represents the fight path, and the grey line represents the estimated tangential point profile.

Based on the Perth – Sydney flight route, the occultation distribution density is calculated as approximately 3 occultations per hours of flight (80 occultation events over 6 flights of a total fly time of 27 hours). This agrees well with the result achieved by Haase and Lense (2001) : 22 occultations for a 8 hours flight. Considering right hand plot of Figure 4, it can be noted that the occultation event is evenly distributed along the flight path.

Figure 5 provides an overview representation of the GPS occultation simulated for all flights on 14 November, 2006. It can be seen that there is very dense occultation observation coverage along the coast line between Brisbane, Sydney, Melbourne, and Adelaide. This is as expected as there are far more frequent flights between these airports compared to others due to population density. There are limited data available in the north and north-west coast, and almost no occultation data is available in some central area of Australia. However, if a higher density is required, flight from other airline carries, such as Virgin Blue and Jetstar could be considered. In addition, international flights from and to Asian Pacific region is also expected to improve data density in the north and north-east region part of Australia.

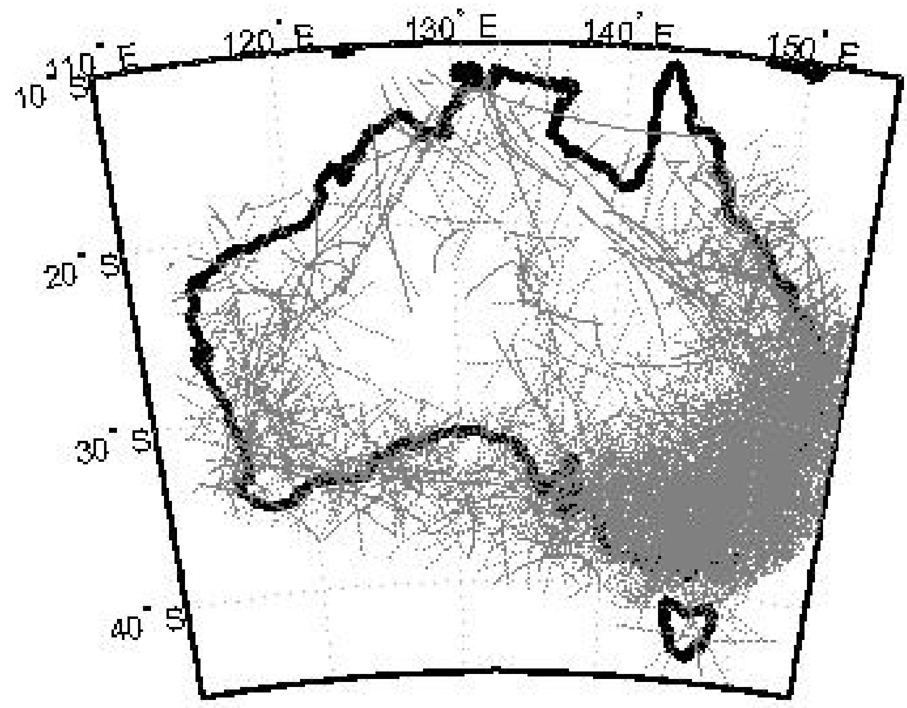

Figure 5. GPS occultation distribution for 14 November, 2006 for Australian region, simulated with direct Qantas flight service.

In addition, the simulated occultation events are analysed with respect to time. Figure 6 shows the time history of both total number of GPS receiver in operation and the total number of occultation points. Results are generated using all of the available flights. As can be shown from Figure 6, there is basically no data available during the early morning (0 – 5am) and data are rapidly decreasing around 9 pm. Although, this result pattern is as expected as results of no flight activities during this period, but this could be one of the limitations of using commercial air services as the airborne GPS occultation platform. The effect of such limitation should be further studied and the impact should be analysed.

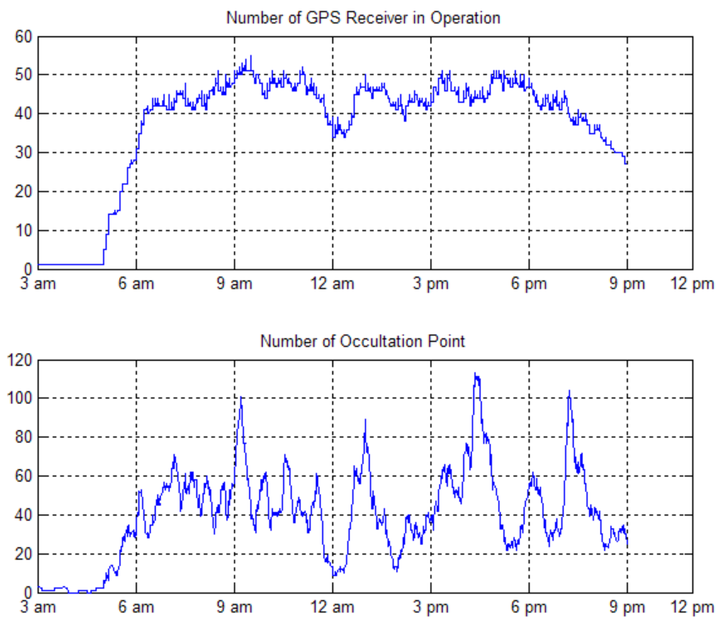

Figure 6. A time history comparison of the number of GPS receivers vs. the number of simulated occultation points on 14 November, 2006

Figure 7 shows one snapshoot of the GPS receiver location and the estimated tangent point location at 9:10am, 14 November, 2006. The 51 GPS receiver locations at this particular time instance is represented by red triangles, the 101 tangential points estimated from the observed occultation events are marked as the black dots. Following the similar pattern, the distribution of both the GPS receiver locations and the tangential points are much more concentrated in the south-east region than other areas.

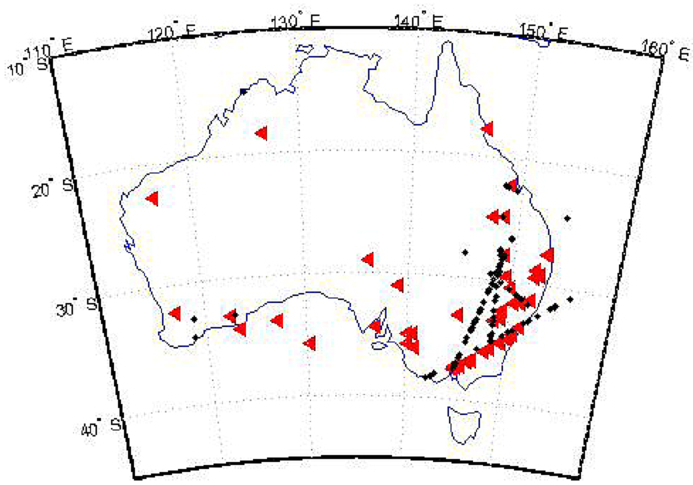

Figure 7. A snapshoot of the GPS receiver points and the simulated occultation points on 9:10 am 14 November, 2006.

4. CONCLUSIONS

The objective of this research was to explore the benefits of airborne occultation approach through simulation study, presenting results for a case study for the Australia region. In the study all direct Qantas flights between fourteen domestic and international airports on 14 November, 2006 were simulated. Based on the GPS satellite constellations and the simulated air-borne platform, occultation events were then estimated along the tangential point profiles. Finally, the occultation distribution was analysed with respect to flight routes as well as with respect to time.

Occultation distribution analysed with respect flight routes has yield result agreed to those presented by previous researchers. Using flight route between Perth and Sydney as a representative for the whole data set, an average of three occultations can be detected per hour. Thus, it is expected to detect 24 occultations for an 8 hours flight. We note that there are much denser occultation observations in high population areas such as coast line along Brisbane to Melbourne. Observations are scattered in the central, north and north-west region of Australia. If a denser observation is required, it is recommended to include flights from other domestic airline carries as well as international flights from and to Asian Pacific regions.

On the other hand, occultation distribution analysed with respect to time shows that the number of occultation observations will be significantly affected during off-peak hours (midnight to early morning). As there are no flight activities from commercial airline carrier, it will certainly have some affects on the application and must be taking into consideration.

Overall, the examined airborne GPS occultation approached has the ability to provide high resolution occultation observations at a cost that cannot be matched by other existing occultation technologies. However, this technique is still in its early stage of studies and development, many technical difficulties still required to be solved. It is hoped that with further research efforts, airborne occultation system can become a complement to the global spaceborne occultation observing systems.

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